PROGRESS WITH THE NAC INJECTOR CYCLOTRON FOR HEAVY AND POLARIZED IONS

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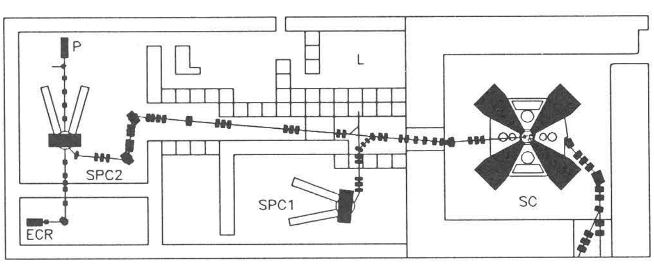
ABSTRACT

The k=11 MeV injector cyclotron under construction at the NAC will produce beams of light and medium heavy ions. Both the ECR source and the atomic beam source for polarized protons and deuterons are now in operation. Magnetic field mapping has been completed and the data processed. The central region of SPC2 has a fixed geometry for the three constant orbit patterns required for acceleration of ions with orbital frequencies between 1 MHz and 13 MHz. Harmonic numbers 2 and 6 will be used. Diagnostic equipment includes 2 differential probes, 2 sets of radial and axial slits, a movable harp, a phase probe and a quartz viewer plate with a TV camera. A versatile vacuum pumping system will allow pressures down to the 10^{-5} Pa range.

1. INTRODUCTION

The second injector facility for the 200 MeV separated-sector cyclotron at the NAC consists of a k=11 MeV solid-pole cyclotron, an ECR source for the production of light and medium-heavy ions and an atomic beam source for polarized protons and deuterons (Fig. 1). The cyclotron itself is very similar to the existing injector cyclotron for light ions, SPC1[1]. Major deviations from the SPC1 design are an axial inflection system, a vacuum system designed for the lower pressures required for the acceleration of heavy ions, modifications to the rf-system to decrease the low frequency limit from 8.6 MHz to 6 MHz and improved beam diagnostics.



KEY:
SPC1: Solid-pole injector cyclotron for light ions
SPC2: Solid-pole injector cyclotron for heavy or polarized ions
SC: Separated-sector cyclotron
ECR: ECR ion source (basement)
L: Low-energy experimental area
P: Polarized-ion source (basement)

Fig. 1. Layout of the cyclotron vaults showing the second injector SPC2 and its ion sources.

Tables 1 and 2 show typical beams and intensities which should be available once the injector is in operation in December 1993.

Table 1. Beam energies and intensities expected from the 200 MeV separated-sector cyclotron with SPC2 as injector.

Element	Energy (MeV/nucleon)		Intensity (pnA)
	Min.	Max.	
^{1}H	30	200	5000
			500
		66	30000
^{4}He	40	220	500
^{15}N	2.6	32.7	>1
^{40}Ar	2.0	19.8	>1
^{84}Kr	2.0	11.25	>1
^{129}Xe	2.0	4.76	>1

Table 2. Available polarization states for proton and deuteron beams.

	protons	deuterons					
pz	±1	-2/3	2/3	0	0	1	-1
pzz		0	0	-2	1	-1	1

2. ION SOURCES

The 10 GHz minimafios ECR source is performing well. Minor modifications were implemented and, apart from the vacuum pumps and valves, it can now be operated via the accelerator control system.

Computer software and hardware were also developed for quick identification of ion spectra behind the analysing magnet, tuning of the source to the requested beam specifications, monitoring and recording of the beam stability, and to keep a database for all the important parameters[2].

The ion source for polarized protons and deuterons is of the atomic beam type. Six 1500 ℓ/s fomblin lubricated turbopumps are used for differential pumping. The atomic beam is formed by a 25 mm long sapphire nozzle which is cooled to 30 °K. Two sextupole magnets are used for deflection of unwanted electron spin components and for beam focusing. The rf-units used to induce transitions between different spin states are located between the sextupoles and/or behind the second sextupole. Table 2 shows the various polarization states that can be obtained. The ionizer is of the well-known ANAC-CERN design.

During the acceptance tests in December 1990 a 28 μA proton beam with an emittance of 135π mm mrad was measured behind the analysing magnet. The polarization of the beam could not be measured as yet. However, the electron polarization is between 80% and 90%.

3. MAGNET

The main magnet of SPC2 is almost identical to that of SPC1[3]. The modifications to allow for the stronger magnetic fields have been described before[4].

Small modifications to the field measuring equipment[5] used for SPC1 were necessary. A new PC-based program has been implemented to make the system more reliable and user-friendly and to improve the protection of the system and the accumulated data.

The following field-setting procedure, which ensures stationary fields before the start of the measurements and reproducibility of the fields in future runs, was used: starting from any value the excitation current is first set to -800 A for 6 min to eliminate remnant fields; then the final current is set via an overshoot of 6 min duration for critical damping of eddy currents.

Field maps, each consisting of 7381 points in the median plane, were measured for 12 values of the main coil excitation current. This covered an average field range at extraction from about 0.3 tesla to 1.1 tesla. In addition, fields were also measured for each of the 8 pole-gap coils (6 trim-coils and 2 cone-coils) at two excitation currents. In total 138 fields were measured.

As a final test, we compiled fields for the reference particles (3.15 MeV protons representing the beams for neutron therapy, 8 MeV protons i.e. maximum energy protons and 47 MeV krypton ions representing the heavy ion beams). The SPC2 power supplies were then set according to the predicted currents for each reference particle and the corresponding fields were measured.

The calculated rf-phase excursions of the reference particles in these fields from injection to extraction do not deviate by more than 2 degrees, indicating good agreement between the requested and the measured fields. The vertical betatron frequencies for these particles are shown vs. the orbital radius in Fig. 2.

Although there is adequate focusing, we found that small deviations from the calculated current settings in the outer trim-coils could cause axial defocusing near the extraction radius.

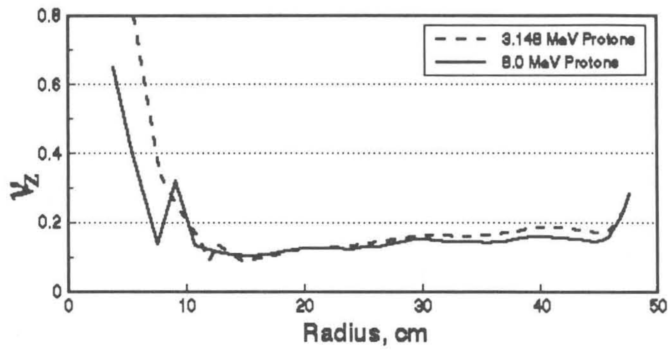


Fig. 2. Graphs showing ν_z vs. orbital radius for 3.148 MeV and 8 MeV protons respectively.

4. CENTRAL REGION

The central region (Fig. 3) has been designed for the acceleration of protons and heavier ions up to xenon. The cyclotron will be operated in constant orbit geometry mode. Three orbit patterns are used, namely 34 turns for protons, 17 turns for the lower-energy proton beams (e.g. beams for neutron therapy and radioisotope production) and for the higher energies of ions such as argon and krypton, and 9-turns for the heaviest ions (i.e. xenon) as well as for the lower energies of the lighter ions. Other design requirements were an acceptance of at least 200π mm.mrad, a vertical betatron frequency ν_z of at least 0.1 and a maximum dee voltage of 60 kV.

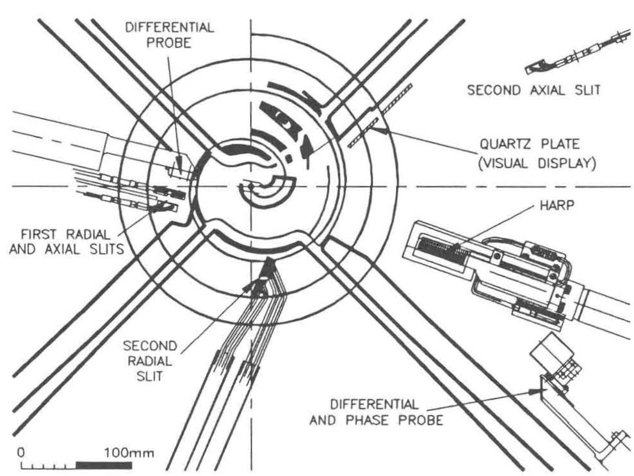


Fig. 3. Layout of the central region of SPC2 showing the first two turns of the 34-turn orbit pattern and the various slits and beam diagnostic equipment.

Switching between orbit modes can be accomplished without ventilating the cyclotron. The entrance slits in the first dee are fixed and the spiral inflectors can be exchanged or serviced in a parking chamber. Those components that have to be adjusted (i.e. diagnostic slits in the central region and extraction elements) are remotely controlled.

The preliminary orbit calculations were carried out using the measured magnetic and electric fields of the first injector cyclotron. From these orbits a model of the central region was designed for measurements in the electrolytic tank[6]. The measured electric and magnetic fields were then used to refine the calculations and obtain the final design orbits. The design particles used for the 34-, 17- and 9-turn orbit patterns were 8 MeV protons, 3.15 MeV protons and 49 MeV Kr^{16+} ions respectively.

The final design orbits were found with the requirement that in the field-free region of the inflector housing, the ion energy must match the injection energy concomitant with the dee potential. Studies of the electrical focusing at the first few gaps showed acceptable results for the 17- and 9-turn orbits, but the re-entry of the 34-turn orbit into the housing proved to be defocusing. The geometry at this crossing was changed so that the condition $\nu_z > 0.1$ was met. The acceptance of the design, excluding the inflector, was determined and proved to be adequate.

The inflectors decided on are of the spiral type. The first designs were studied using the analytic model. The physical limitation imposed by the pole gap necessitated tilting of the inflector electrodes. Form factors for the electric field seen by the design particle were evaluated by means of the code RELAX3D[7]. This field was then used by the code SPICE to calculate the orbit for a specific set of inflector parameters. The program uses either the steepest descent or the Broyden algorithm to optimize the fit of the inflector design orbit to the cyclotron design orbit. The program requires the inflector to inject the ion in the median plane of the cyclotron with no vertical component of momentum and with a radius of curvature matching that of the cyclotron design orbit. The inflector parameters allowed to vary are the inflector electrical radius, the electrical field strength, and the electrode tilt. The resultant design is then rotated to match the centres of curvature, and the parameters found are inspected to verify that they are physical acceptable. The electrode surfaces are approximated by a set of ruling lines. These can be visually inspected on the microcomputer screen.

5. RF-SYSTEM

Most components of the SPC2 rf-system, including the phase and amplitude stabilization systems and the control system, are similar to those of SPC1. The two power amplifiers have been redesigned to cover the frequency range from 6 to 26 MHz. Two ports were provided on each resonator for the additional stub lines[4] required for covering the 6 to 8.6 MHz range in two steps. This results in lower current densities compared to the use of a single stub line.

6. DIAGNOSTICS

All the diagnostic equipment installed in SPC1, i.e two differential probes, two radial slits and two axial slits as well as various collimators and insulated components on the extraction channels, are duplicated in SPC2[1,3]. However, some modifications to the original designs, as well as additional diagnostic equipment were required. The second differential probe, with current measurement on three fingers and the body itself, was modified to include a phase probe head on the tip of the probe (Fig. 3) and the indirectly water-cooled second radial slit situated in the second dee is replaced by a directly water-cooled slit.

The additional diagnostic equipment is a stepping motor driven harp consisting of 47 vertically mounted wires, spaced 1 mm apart, which will enable us to determine the horizontal beam profile and position of the orbits from a radius of about 200 mm right up to the extracted orbit in front of the second extraction channel. A quartz plate situated in the central region, viewed through a TV camera and pivoted into the beam plane will provide this information on the first turns.

A four-segmented aperture will be installed in front of the inflector to restrict the beam size and provide limited position information. We also intend to install a four-segmented capacitive pick-up probe in the magnet pole which will be used as a non-invasive beam position and intensity probe.

7. VACUUM SYSTEM

Detailed calculations were made in an attempt to improve the efficiency of the SPC2 vacuum system[4]. Pressures in the 10^{-5} Pa range will only be needed occasionally for the acceleration of highly charged heavy ions and an expensive pumping system cannot be justified for this purpose. The pressure distribution for the previously proposed system was first re-calculated, using more realistic values for the conductance, aperture and applied pumping speed. This result was compared with pressures computed for a new system consisting of one 2.2 m^3/s turbopump, a 10 m^3/s cryopump and a liquid nitrogen (LN_2) cryopump with a pumping speed of 18 m^3/s for water vapour at the far end of each resonator. It shows that a negligible increase in the pressure at the cyclotron centre will result from using a

10 m^3/s cryopump on the main vacuum chamber instead of the 18 m^3/s cryopump specified previously. Secondly, a more significant reduction in the pressure is predicted if the two 2.2 m^3/s turbopumps at the resonator ends are replaced by two LN_2 cryopumps.

Figure 4 depicts results of calculations for both systems. The effect of three different pump combinations on the pressure distribution for the new system is also shown. A pressure of 6.3×10^{-4} Pa will be obtained in the beam region using only the 2.2 m^3/s turbopump. This pressure will suffice for acceleration of protons. With the help of the 10 m^3/s cryopump the pressure will be reduced to 2.9×10^{-4} Pa, for the acceleration of light heavy ions. Adding also the LN_2 cryopumps will result in the lowest operational pressure of 8×10^{-5} Pa. This pressure is necessary for adequate transmission of heavy ions. For the LN_2 cryopump option, two additional inexpensive pumps which have a high pumping speed for air are required. Oil-diffusion pumps with a pumping speed of 1.75 m^3/s should be adequate for this purpose.

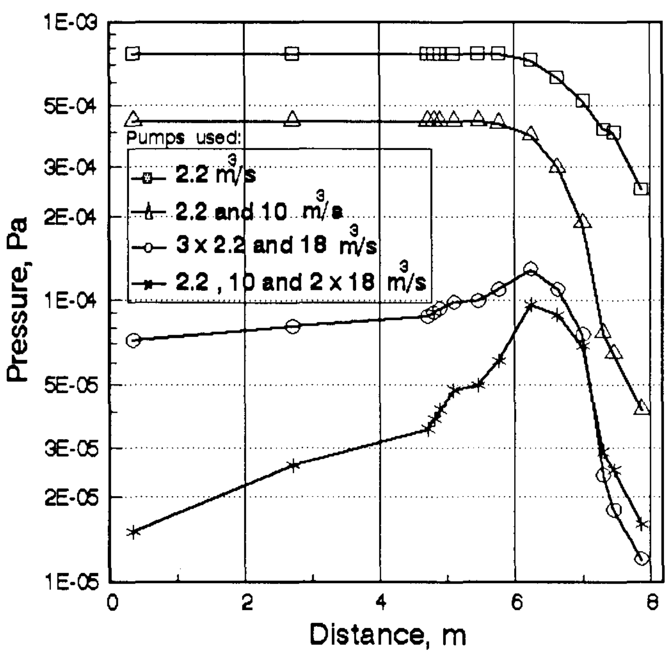


Fig. 4. Calculated pressure distribution in SPC2 for various pumping combinations. The zero length indicates the position of the resonator far end.

8. ACKNOWLEDGEMENTS

The authors would like to thank L.H.O. Schülein and J.G. de Villiers of the NAC Magnet Division and J.L.G. Delsink of the NAC mechanical workshop for their assistance.

9. REFERENCES

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